Hadronic Modeling of AGN Variability

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Unified Model
The Emission of Blazars

Markarian 501 multifrequency campaign 2009\(^1\):

- typical double hump structure
- from radio to gamma-rays
- peak frequencies and flux levels vary

\(^1\)from Abdo et al. 2011
The Emission of Blazars

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PKS 2155-304 [Aharonian et al., ApJL 664 (2006)]

\(^1\)from Abdo et al. 2011, \(^2\)from Albert et al. 2007
The Debate

- optical to hard X-Ray peak: doppler enhanced synchrotron radiation
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- High luminosity blazars (e.g. FSRQs): simple SSC fails, require:
  - compton upscattering of external photons
  - hadronic synchrotron radiation and subsequent cascades
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- optical to hard X-Ray peak: doppler enhanced synchrotron radiation
- Low luminosity blazars (mostly BL Lacs): well described by the Synchrotron Self-Compton mechanism
- High luminosity blazars (e.g. FSRQs): simple SSC fails, require:
  - compton upscattering of external photons
  - hadronic synchrotron radiation and subsequent cascades
- strongly dependent on the emitting site within the jet (within the broad line region or beyond)
Demands on the Model

Unbiased hybrid emission model

- allow for non-thermal leptons and hadrons to be relevant emitters in the jet
- determine dominating species during the modeling
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Selfconsistency

- assume no input particle spectra
- particle spectra must arise from acceleration and cooling

Timedependency

- exploit the full information we get from blazar-emission
The Model I

Assume spherical emitting and acceleration region containing isotropic particle distributions and randomly orientated magnetic field in a nested setup:

Kinetic equation: acceleration zone

\[
\partial_t n_e = \partial_\gamma \left[ (\beta_s \gamma^2 - t_{acc}^{-1} \gamma) \cdot n_e \right] + \partial_\gamma \left[ \left( (a + 2) t_{acc} \right)^{-1} \gamma^2 \partial_\gamma n_e \right] + Q_0 - t_{esc}^{-1} n_e
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see M. Weidinger et al. 2010 for details
The Model I

Kinetic equation: radiation zone

\[
\partial_t N_e = \partial_\gamma \left[ (\beta_s \gamma^2 + \gamma IC) \cdot N_e \right] + t_{esc}^{-1} n_e - t_{esc,N}^{-1} N_e
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Photon distribution

\[
\partial_t N_{\text{ph}} = R_{\text{syn}} + R_{\text{IC}} - c\alpha_{\text{SSA}} N_{\text{ph}} - t_{\text{esc,ph}}^{-1} N_{\text{ph}}
\]

Selfconsistent SSC limit
see M. Weidinger & F. Spanier 2010 for details
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Kinetic equation:

\[ \partial_t N_e = \partial \gamma \left[ (\beta_s \gamma^2 + \dot{\gamma}_{IC}) \cdot N_e \right] + t^{-1} \text{esc}_e - t^{-1} \text{esc}_e N_e \]

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Selfconsistent SSC limit:

\[ \dot{\gamma}_{IC} = mc^3 \int_0^{\epsilon_{\text{max}}} d\epsilon_1 \epsilon_1 \int_0^{\infty} d\epsilon N_{\text{ph}}(\epsilon) \sigma(\epsilon_1, \epsilon, \gamma) \]

see M. Weidinger & F. Spanier 2010 for details
Hadronic Interactions

Unlike $e^-$, $p^+$ are not elementary particles $\Rightarrow$ many interaction branches besides synchrotron (and IC) from primary $e^-$ and $p^+$. 

![Diagram showing interactions between $e^-$ and IC: $\gamma$](image)
Unlike $e^{-}$, $p^{+}$ are not elementary particles ⇒ many interaction branches besides synchrotron (and IC) from primary $e^{-}$ and $p^{+}$.

photo meson production

Proton synchrotron

$p\gamma\ CS$ [Hüffer et al., ApJ 721 (2010)]
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*photo meson production*  *Bethe-Heitler pair prod.*

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*photo meson production*

Proton synchrotron

Muon lifetime
Hadronic Contributions

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ / $\overline{\nu}_\mu$

$\pi^0 \rightarrow \gamma + \gamma$

$\gamma + \gamma \rightarrow e^+ + e^-$ (e±-Synchrotronstr.)

Proton synchrotron emission must be relevant.

Requires $p^+ \gamma > \Delta$ to be present in the jet.

$\gamma \approx 10^7 - 10^9$
**Hadronic Contributions**

- $e^{\pm}$-synchrotron
  
  $\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}/\bar{\nu}_{\mu} \rightarrow \pi_{0} \rightarrow \gamma + \gamma$

  Contribution

  Pair cascades with low $\nu$ photons

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  $e^\pm + \nu_e/\bar{\nu}_e + \bar{\nu}_\mu/\nu_\mu$

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- $e^\pm$-synchrotron
  \[ \pi^\pm \rightarrow e^\pm + \nu \]
  \[ e^\pm + \nu \rightarrow e^\pm + \nu \]
- $\pi^0 \rightarrow \gamma + \gamma$
- Pair cascade with low $\nu$ photons
  \[ \gamma + \gamma \rightarrow e^+ + e^- \] (e$^\pm$-Synchrotron)
- Proton synchrotron emission must be relevant

Requires $p^+$ with $\gamma > \Delta^+ / E_{\text{photons}} \approx 10^7 - 10^9$ to be present in the jet.
Now there are 4 **non-linear coupled** equations in the radiation zone:

**Kinetic equations: radiation zone**

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\begin{align*}
\partial_t N_{p^+} &= \partial_\gamma \left[ \beta_p \gamma^2 \cdot N_{p^+} \right] + b^3 t^{-1}_{esc,p} n_{p^+} - t^{-1}_{esc,p,N} N_{p^+} \\
\partial_t N_{e^-} &= \partial_\gamma \left[ (\beta_e \gamma^2 + \gamma_{IC}) \cdot N_{e^-} \right] + b^3 t^{-1}_{esc,e} n_{e^-} + Q_{pp} + Q_{p\gamma^-} - t^{-1}_{esc,e,N} N_{e^-} \\
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**Photon distribution**

\[
\partial_t N_{ph} = R_{syn} + R_{IC} + R_{\pi^0} - c \left( \alpha_{SSA} + \alpha_{pp} \right) N_{ph} - t^{-1}_{esc,ph} N_{ph}
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- Kelner Aharonian parameterization of the SOPHIA Monte Carlo results is used to calculate \(Q_{p\gamma^-}, Q_{p\gamma^+}, R_{\pi^0}\) ⇒ no unstable intermediates \((\pi^\pm, \pi^0, \mu^\pm)\) taken into account
Now there are 4 non-linear coupled equations in the radiation zone:

### Kinetic equations: radiation zone

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\begin{align*}
\frac{\partial}{\partial t} N_{p^+} &= \partial_\gamma \left[ \beta_p \gamma^2 \cdot N_{p^+} \right] + b^3 t_{esc,p}^{-1} n_{p^+} - t_{esc,p,N}^{-1} N_{p^+} \\
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### Photon distribution

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- Cascades will emerge in the optically thick regime \( > 10^{28} \) Hz
SSC limit

For small $B$-Fields and $Q_p \to 0$: SSC case, but selfconsistent

PKS 2155-30.4, $z = 0.117$
see M. Weidinger & F. Spanier 2010(I) for details

1 ES 1218+30.4, $z = 0.182$
see M. Weidinger & F. Spanier 2010(II) for details

Mkn501, $z = 0.034$
1 ES 1011

Intermediate frequency peaked BL Lac object @ z = 0.212

<table>
<thead>
<tr>
<th>Q₀ (cm⁻³)</th>
<th>B (G)</th>
<th>Rₐcc (cm)</th>
<th>R₉rad (cm)</th>
<th>tₐ/tₑ</th>
<th>δ</th>
<th>γ₀</th>
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<tbody>
<tr>
<td>7.50 · 10⁴</td>
<td>0.18</td>
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Outburst of 1 ES 1011

Injection of more primary $e^-$ and $p^+$ for $\Delta t \approx 4$ h.
UHECRs

Fluxes of Cosmic Rays

Flux (m^2 s^-1 GeV^-1)

Energy (eV)

Galactic

Extragalactic

(1 particle per m^2-second)

Knee
(1 particle per m^2-year)

Ankle
(1 particle per km^2-year)
Conclusions and Outlook

- Fully selfconsistent hybrid emission model for blazars
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Consistent treatment of different blazars allows for multi-messenger interpretation of diffuse phenomena (i.e. neutrinos, cosmic rays)